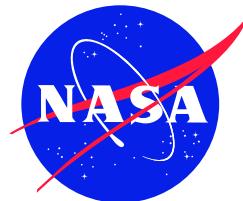


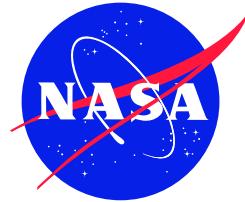
Simulation of a Synthetic Jet in Quiescent Air using TLNS3D Flow Code

Veer N. Vatsa and Eli Turkel



NASA Langley Research Center, Hampton, VA
Tel-Aviv University, Israel and NIA, Hampton, VA

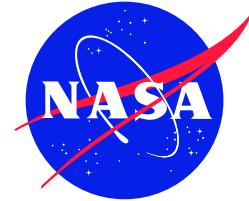
**CFD Validation of Synthetic Jets and
Turbulent Separation Control Workshop
March 29–31, 2004, Williamsburg, Virginia**



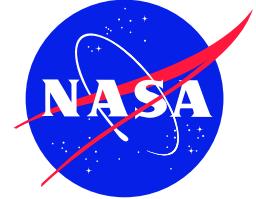
MOTIVATION / APPROACH

- Increase our understanding of flow physics associated with zero net mass transfer control devices
- Assess feasibility of using a compressible URANS code to simulate such flows
- Conduct numerical experiments to quantify spatial and temporal truncation errors
- Examine the effect of one- and two-equation turbulence models on the CFD solutions

Governing Equations and Solution Procedure used in TLNS3D



- Unsteady Reynolds-averaged Navier-Stokes (URANS) equations
 - Generalized thin-layer approximation
 - Conservation law form, body fitted coordinates
 - Multi-block structured grids
 - Spalart-Allmaras (SA) and Menter's SST turbulence models
- Finite-volume, central difference scheme
 - Scalar and matrix form of artificial dissipation added for stability
 - Multistage R-K scheme
 - Variable coefficient implicit residual smoothing
 - Local time stepping
 - Multigrid acceleration technique



Temporal Discretization

Consider the time dependent equation in dual time-stepping form

$$\frac{\partial w}{\partial \tau} + \frac{\partial w}{\partial t} + R = 0$$

where w is general set of unknowns

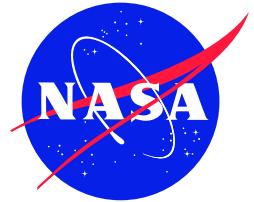
t is the physical time and τ is an artificial time

R denotes the steady Navier-Stokes residual

Replace the physical time derivative by a general backward difference formula (BDF).

$$\frac{\partial w}{\partial t} \sim \frac{c_t w^{n+1} - F(w^n, w^{n-1}, \dots)}{\Delta t}$$

where c_t is the coefficient of the lead time term



Temporal Discretization cont. 1

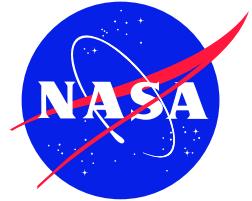
A typical stage of the RK to advance the solution is:

$$w^{k+1} = w^0 - \alpha_k \Delta\tau \left\{ R^k + \frac{c_t w^{n+1} - F(w^n, \dots)}{\Delta t} \right\}$$

where, k denotes the last known stage of RK, $k + 1$ the next RK stage
The superscript 0 denotes the last artificial time step, n the last physical time step, $n + 1$ the next physical time step

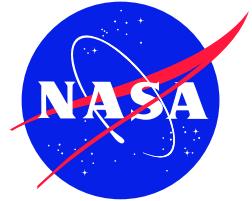
We replace $n + 1$ by $k + 1$ (i.e. current stage of RK) and rearranging the terms, the “update” procedure takes the form:

$$(I + \alpha_k c_t \frac{\Delta\tau}{\Delta t}) w^{k+1} = w^0 - \alpha_k \Delta\tau \left\{ R^k + \frac{c_t w^k - F(w^n, \dots)}{\Delta t} \right\} + \alpha_k c_t \frac{\Delta\tau}{\Delta t} w^k$$



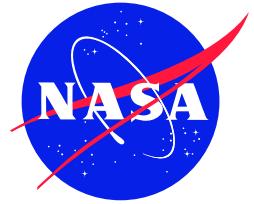
Boundary Conditions

- For the region outside the actuator
 - Lower surface: standard viscous wall conditions (zero slip, zero injection, adiabatic wall, zero pressure gradient)
 - Side surfaces: symmetry conditions
 - Upper boundary: far-field Riemann invariants
- For actuator interior
 - Moving diaphragm: Top-hat sinusoidal velocity (450 Hz.) to produce peak velocity of $M=0.1$ at the jet exit
 - Other walls: standard viscous wall conditions
- Interface condition: C^0 continuity



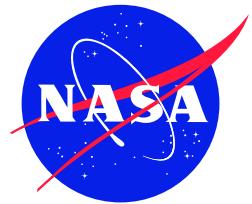
2-D Test cases

- Baseline: SA turbulence model, 72 time steps/period on workshop (structured) grid # 1 (unless mentioned otherwise)
- cg: Coarse grid, every other point from workshop grid # 1
- fg: 50% finer spacing than workshop grid # 1 in normal direction
- low dt: Half of baseline time-step (144 time steps/period)
- SST: Menter's 2-eqn. SST turbulence model

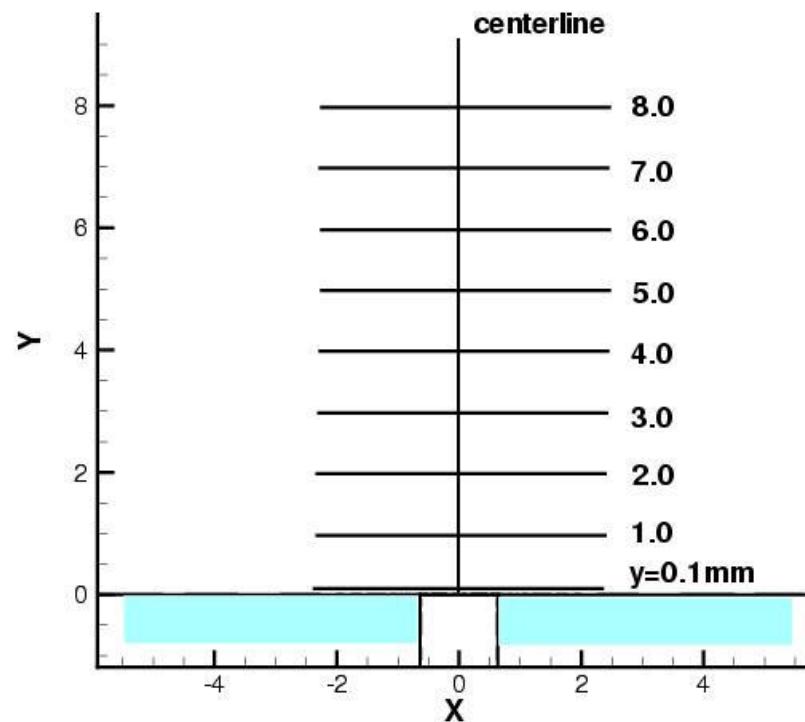


Results

- Time-averaged solutions: Run the code enough time-steps to establish periodicity. Calculate average of field solutions over next 15-20 complete periods.
- Phase-averaged solutions: Obtained from last complete period

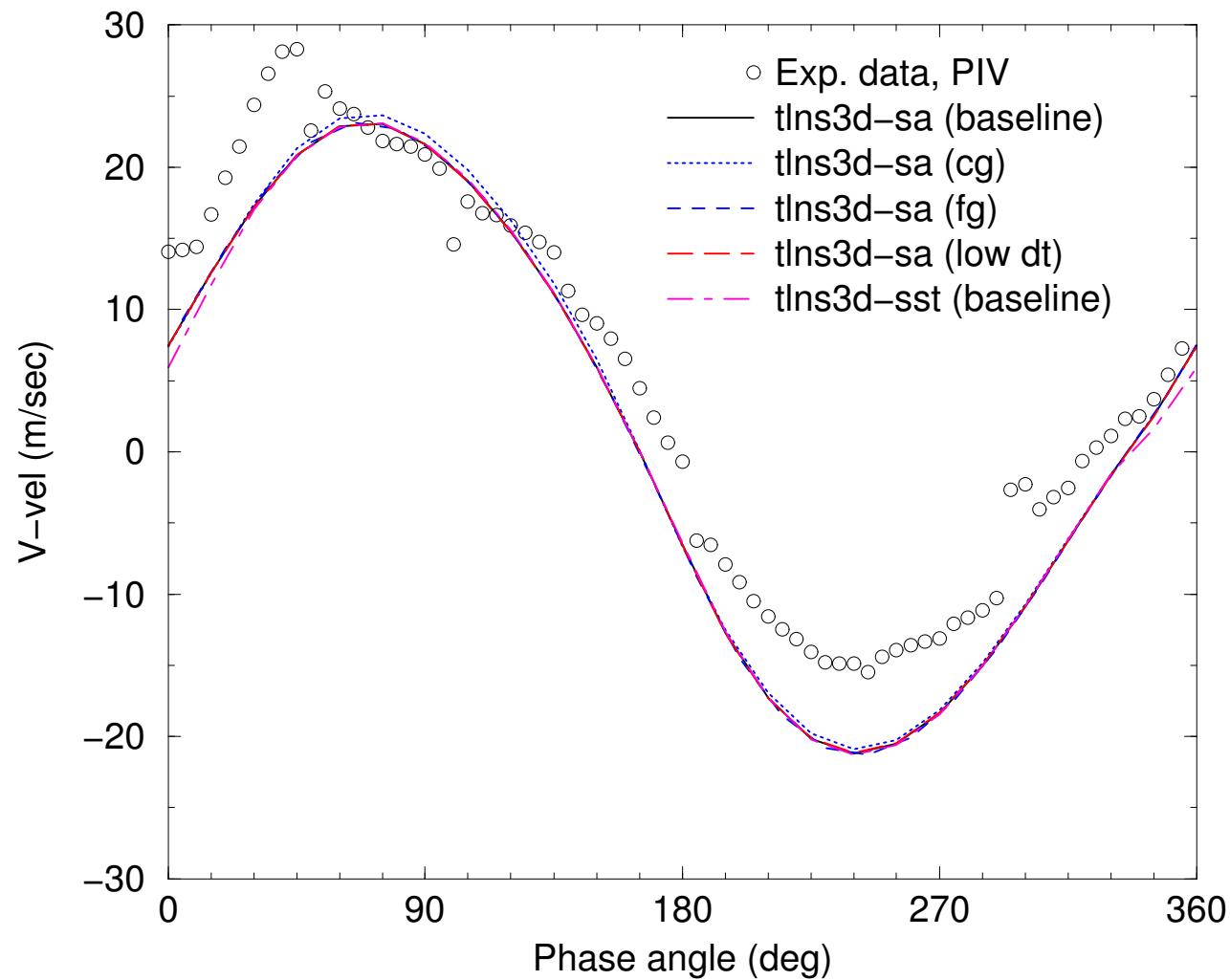


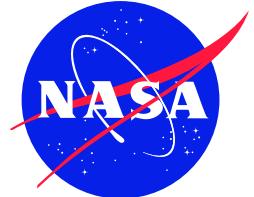
Schematic of actuator



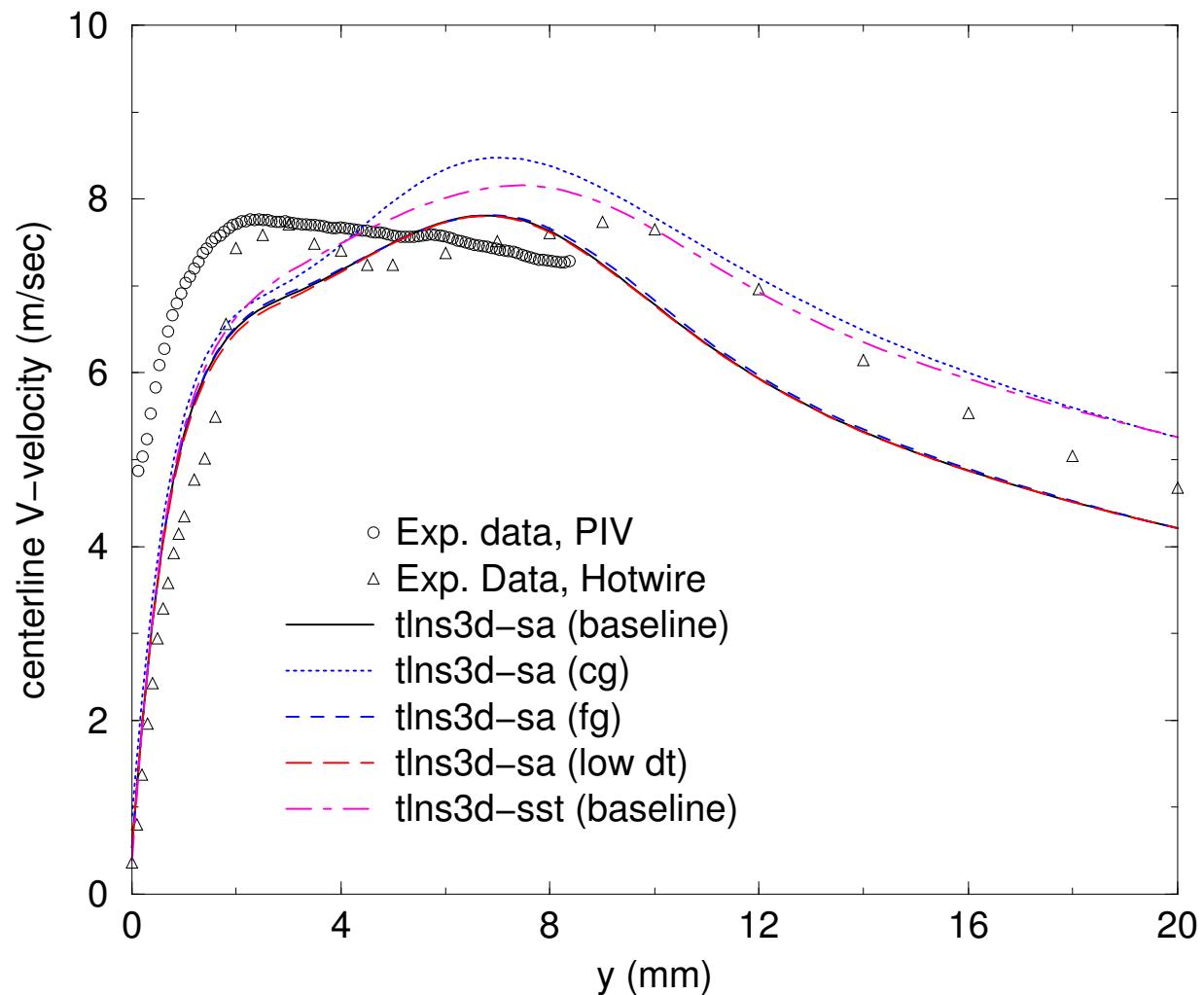


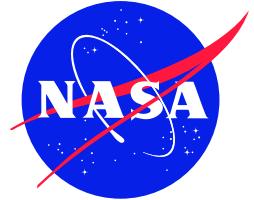
Initial conditions at jet exit ($x=0$, $y=0.1$ mm)



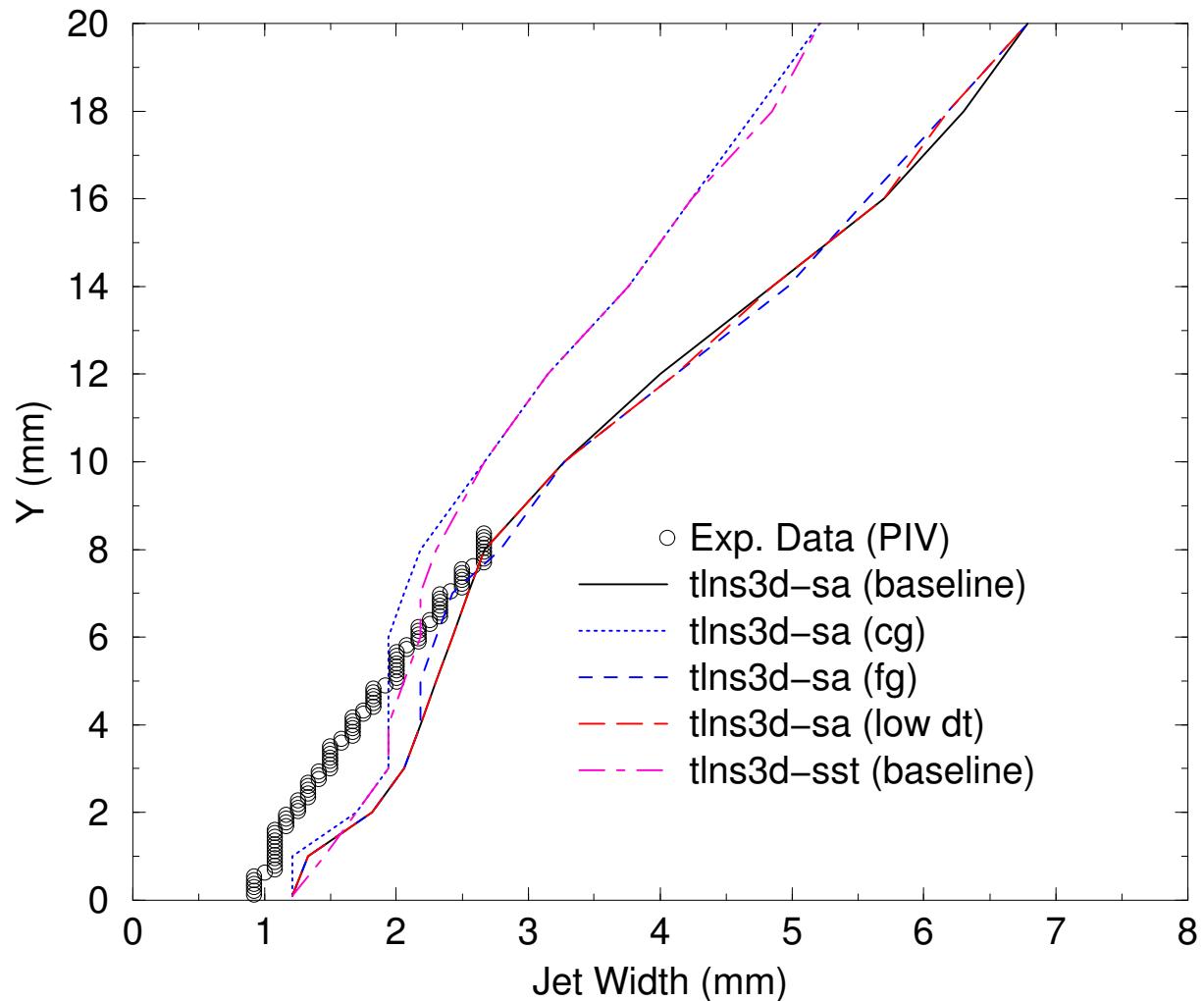


Time-averaged centerline v-velocity



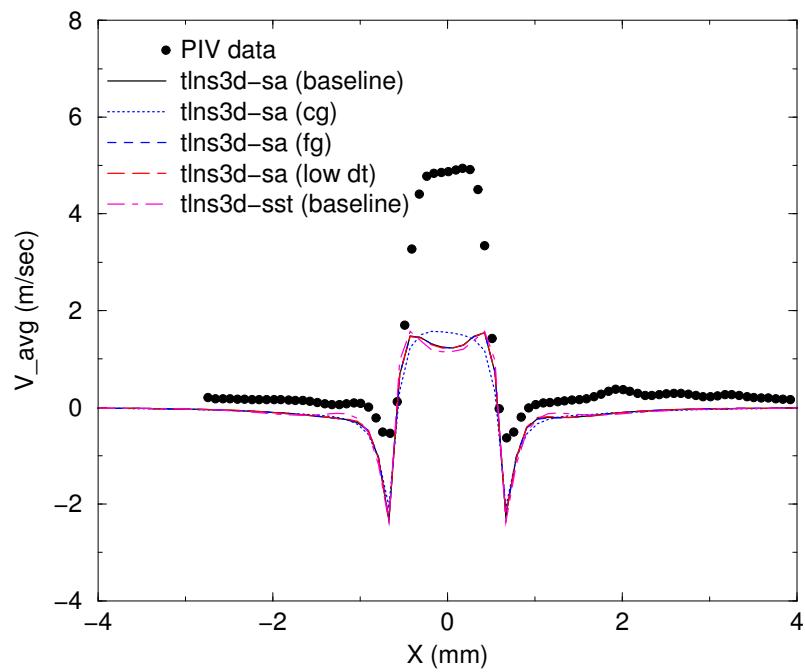


Time-averaged jet-width

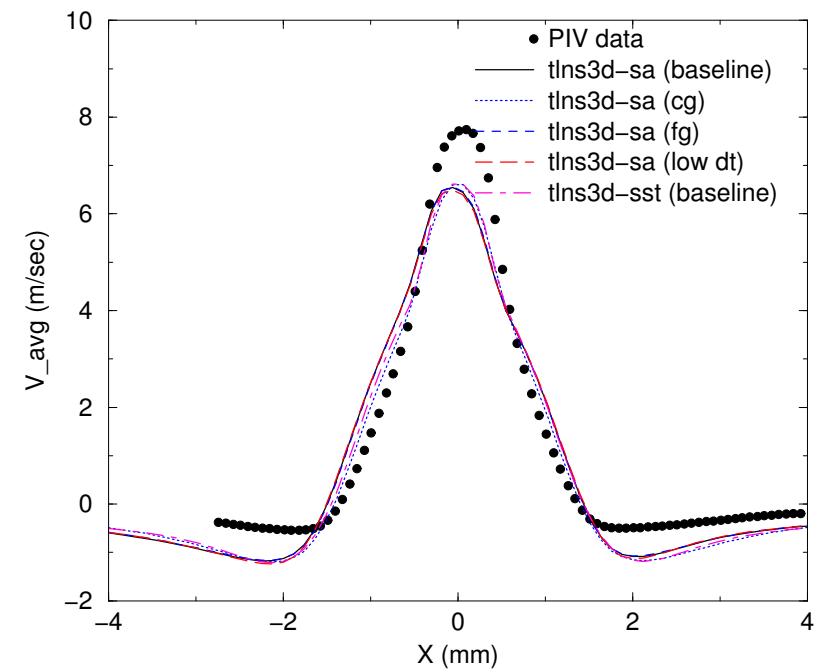




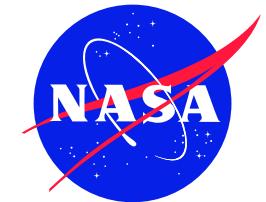
Time-averaged v-velocity profiles



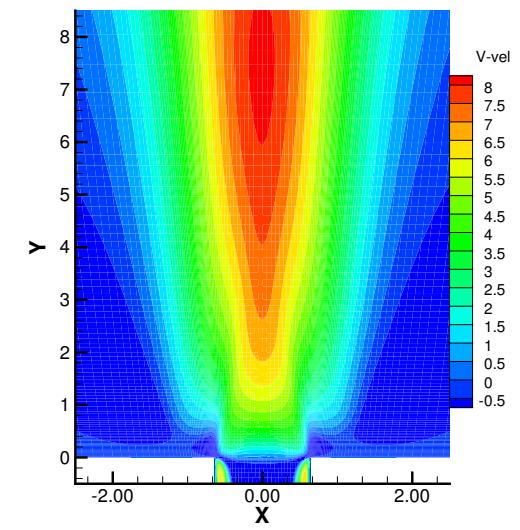
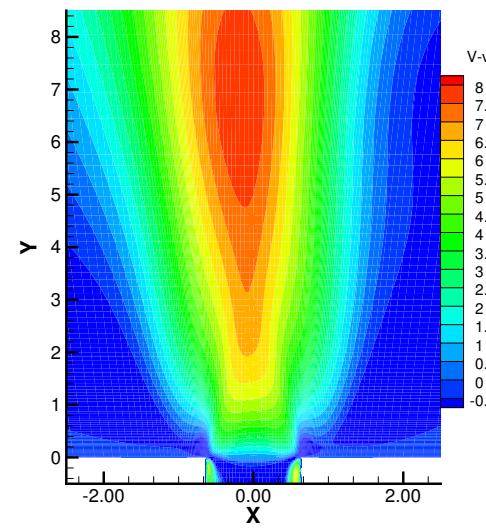
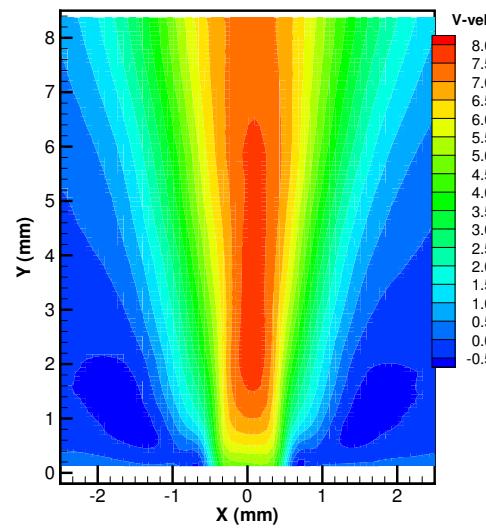
$y=0.1$ mm

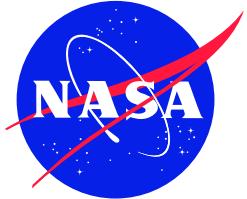


$y=2$ mm

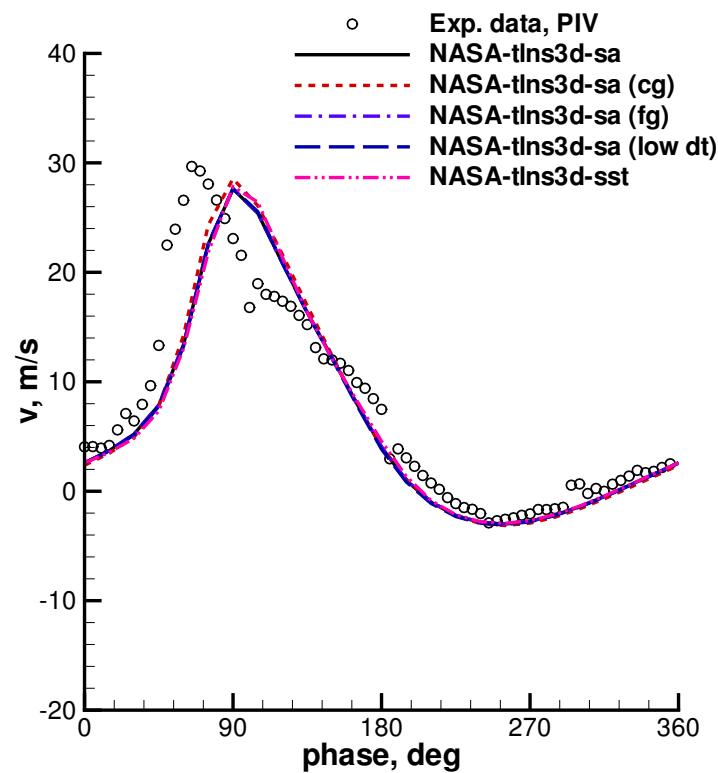


Time-averaged vertical velocity contours

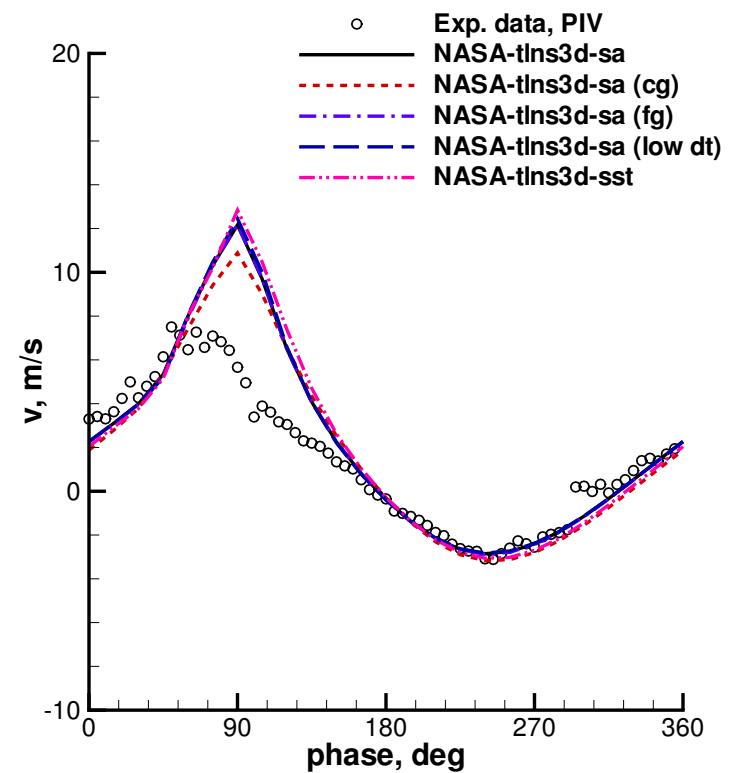




Time-history of phase-averaged v-velocity



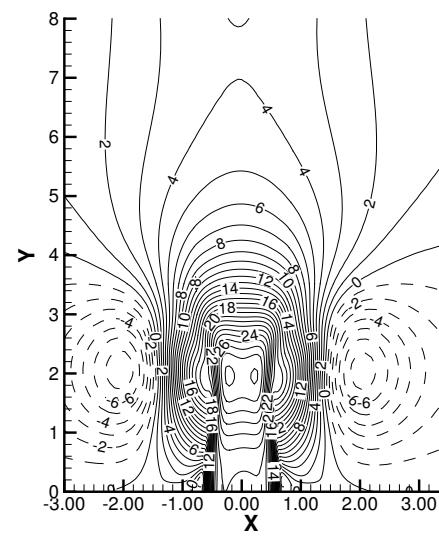
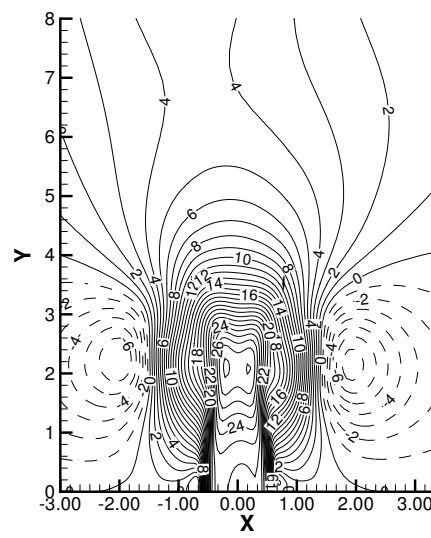
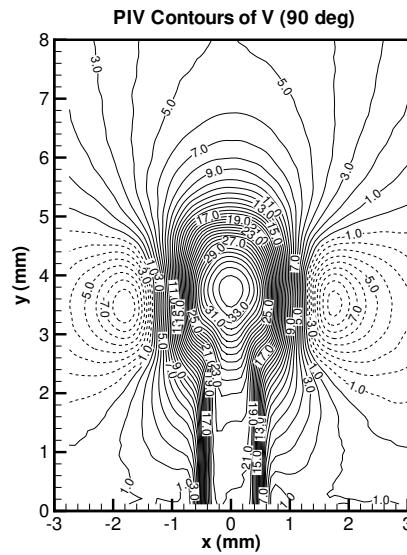
$x=0$, $y=2$ mm



$x=1$, $y=2$ mm



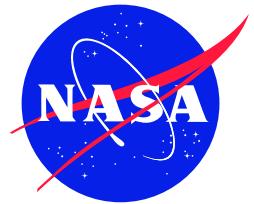
Phase-averaged v-velocity contours, phase=90



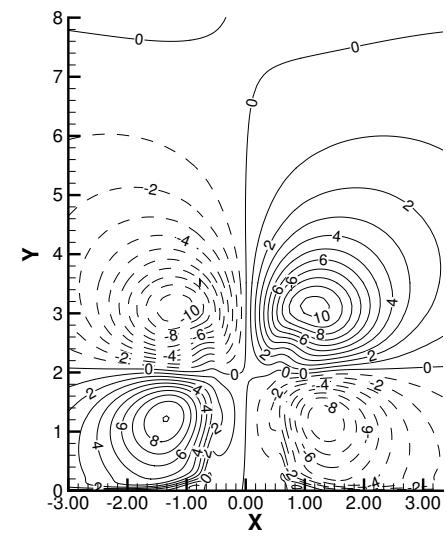
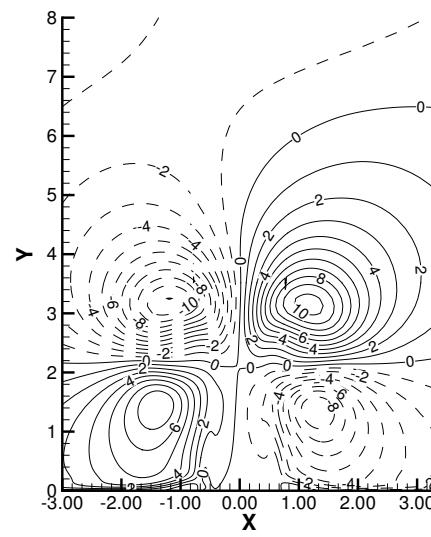
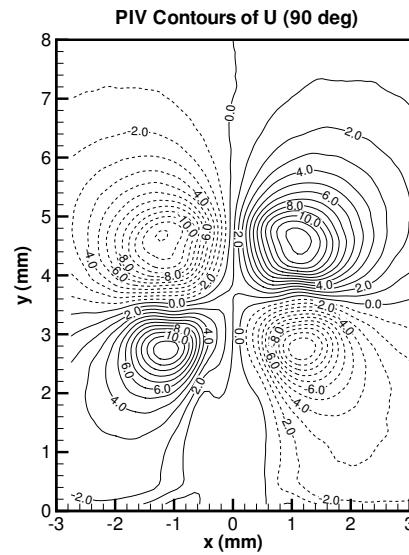
PIV measurements

TLNS3D: SA model

TLNS3D: SST model



Phase-averaged u-velocity contours, phase=90

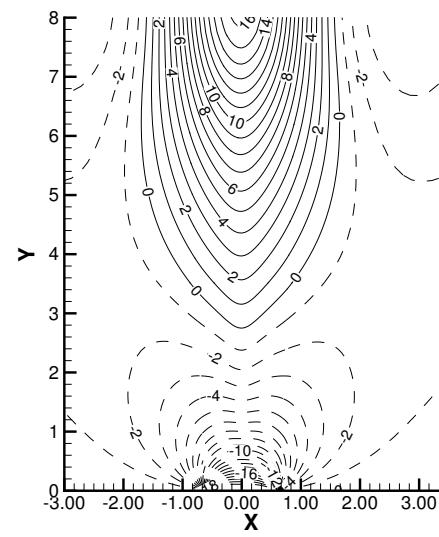
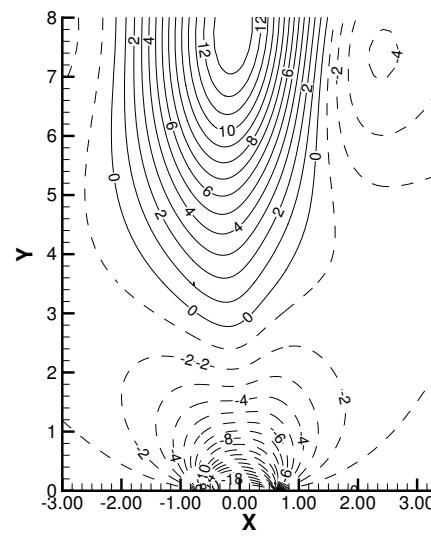
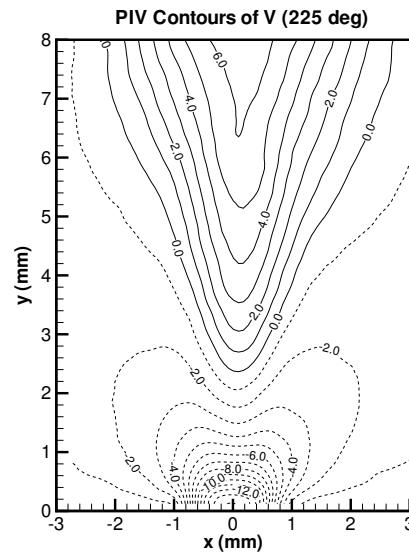
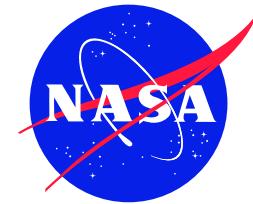


PIV measurements

TLNS3D: SA model

TLNS3D: SST model

Phase-averaged v-velocity contours, phase=225

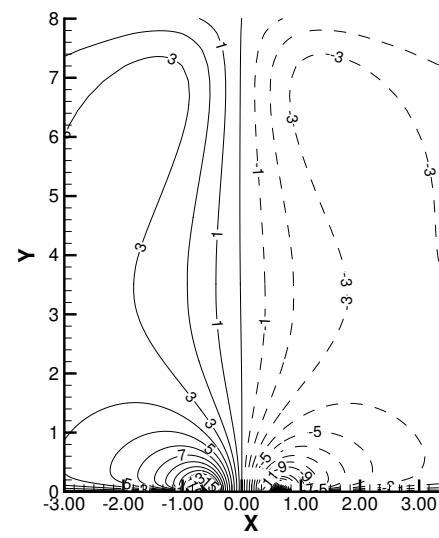
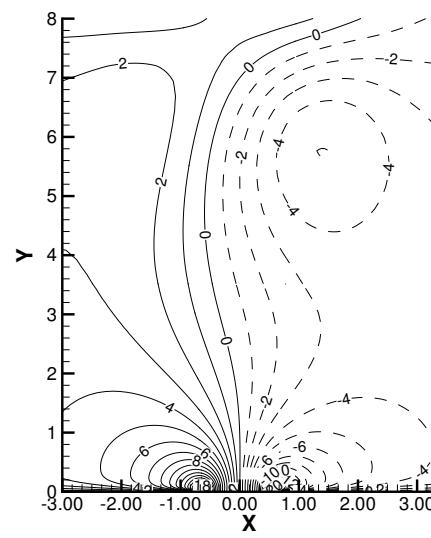
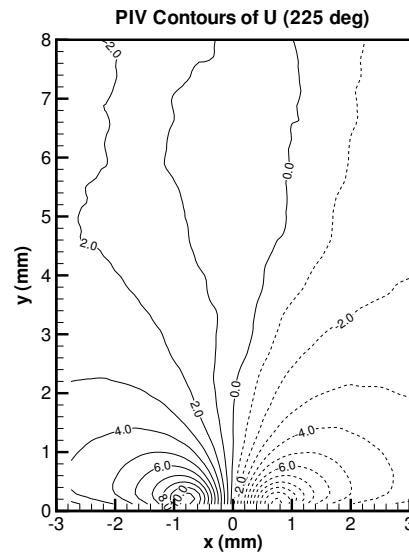
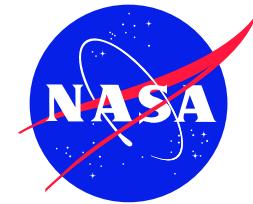


PIV measurements

TLNS3D: SA model

TLNS3D: SST model

Phase-averaged u-velocity contours, phase=225

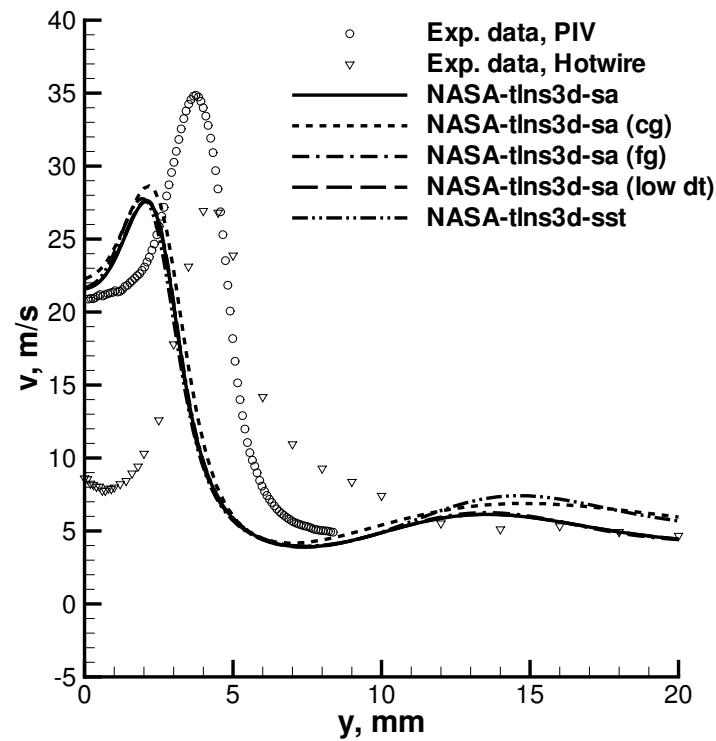
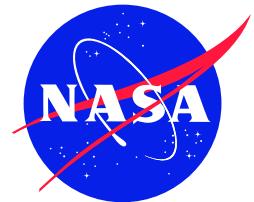


PIV measurements

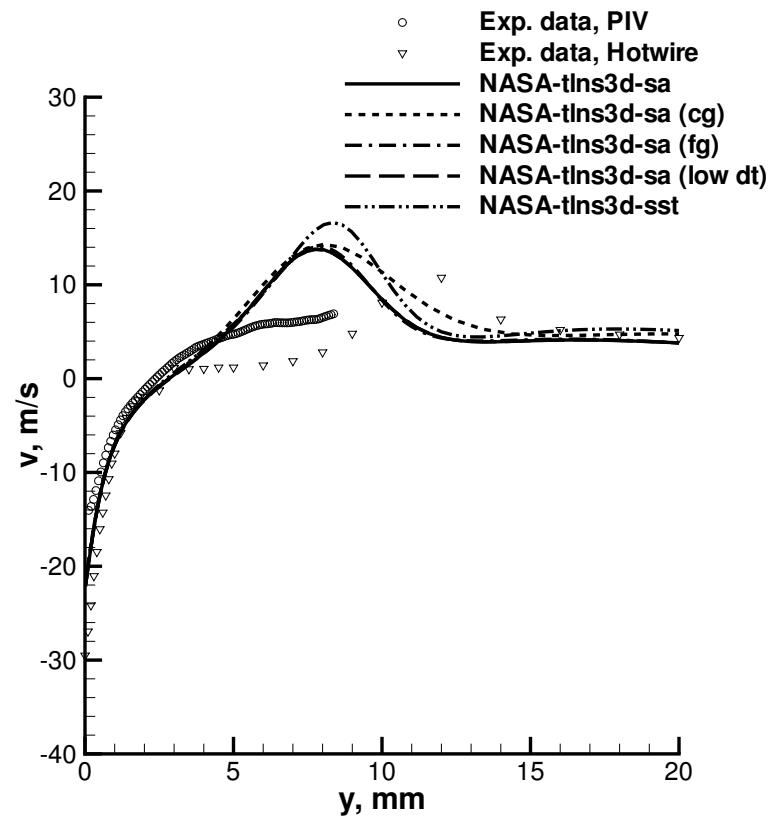
TLNS3D: SA model

TLNS3D: SST model

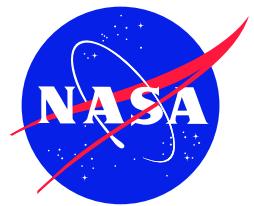
Phase-averaged centerline v-velocity for maximum expulsion and suction



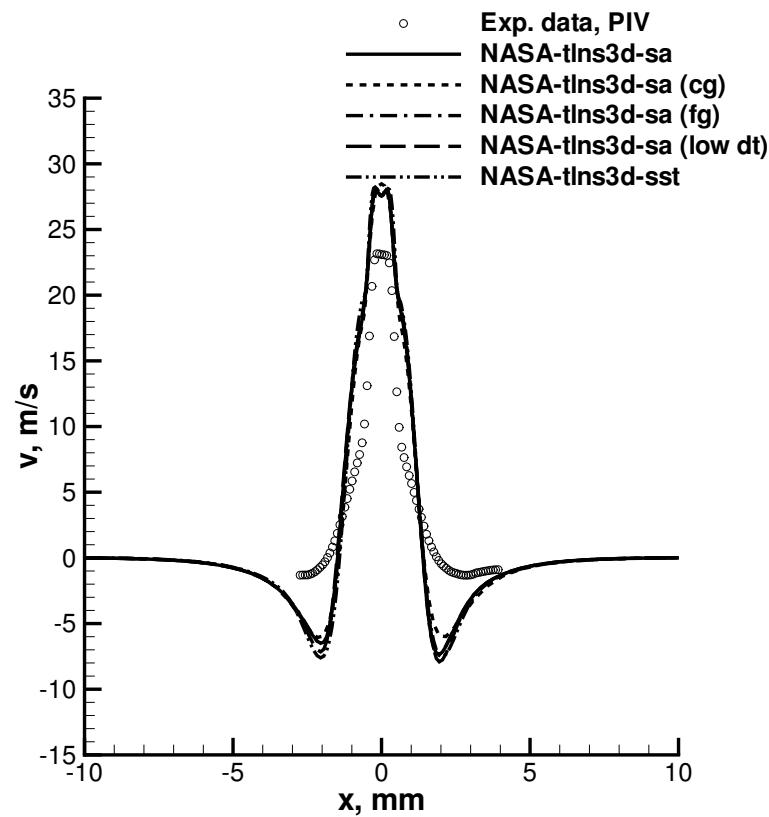
phase=90



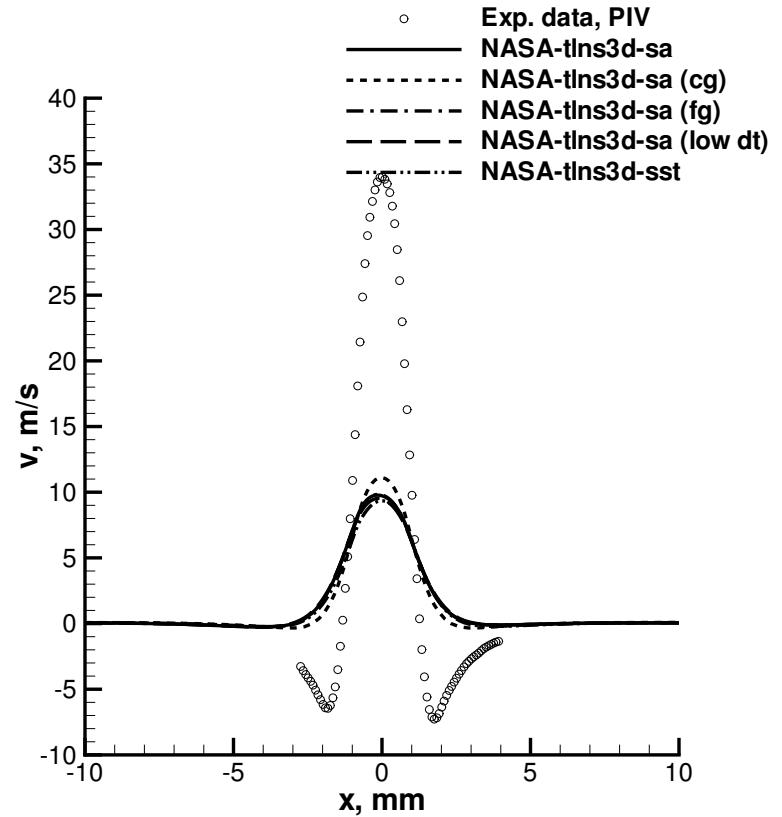
phase=225



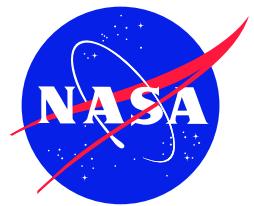
Phase-averaged v-velocity profiles, phase=90



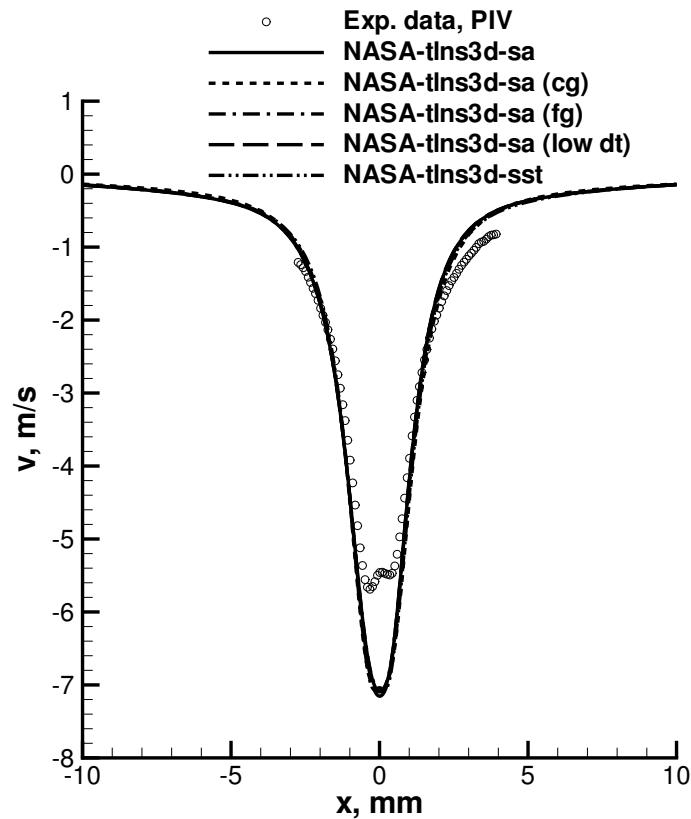
$y = 2 \text{ mm}$



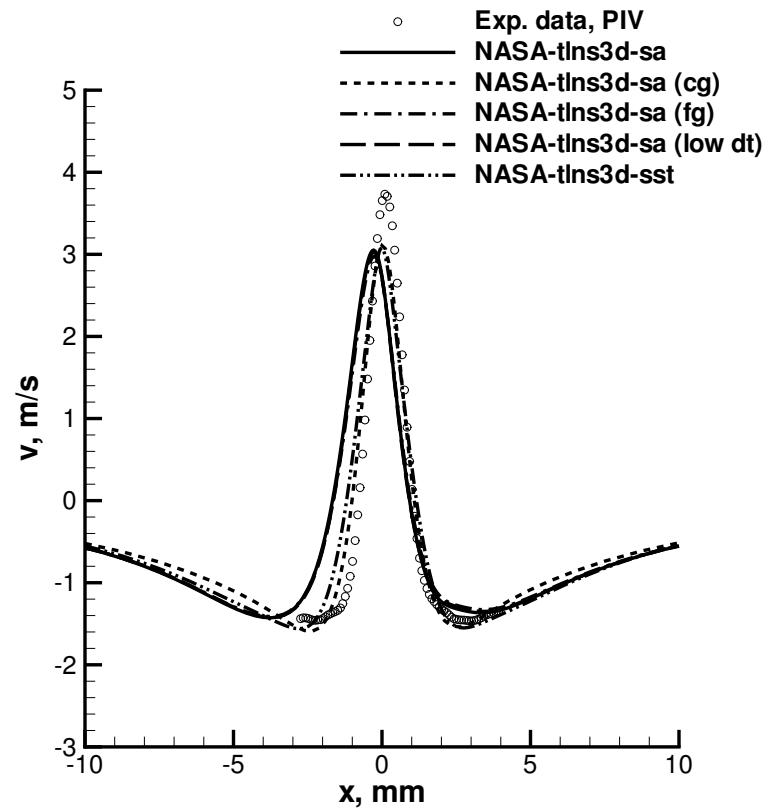
$y = 4 \text{ mm}$



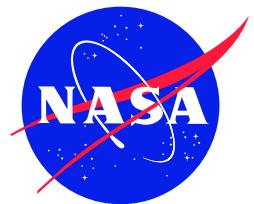
Phase-averaged v-velocity profiles, phase=225



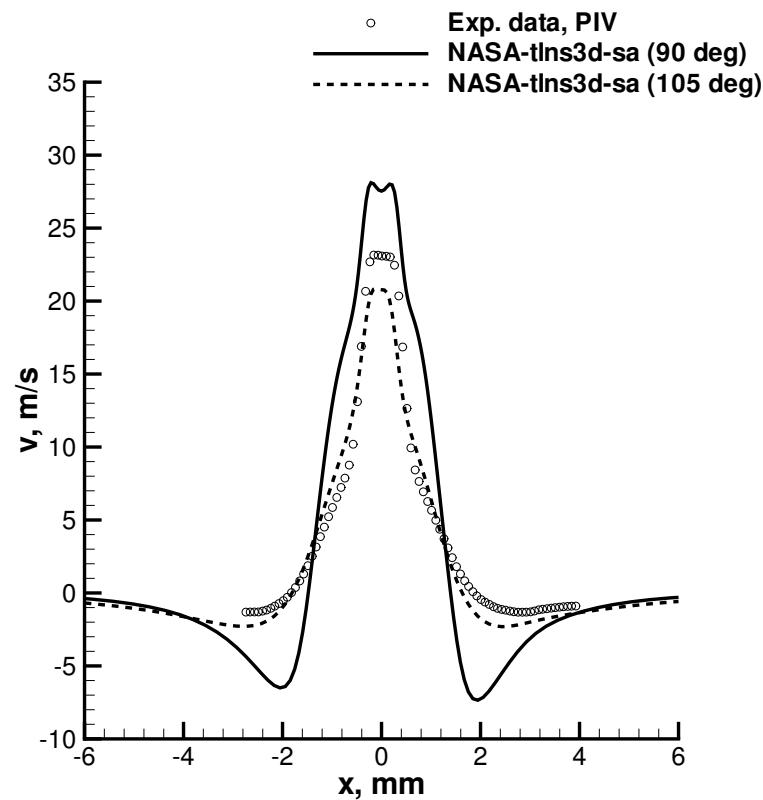
$y = 1 \text{ mm}$



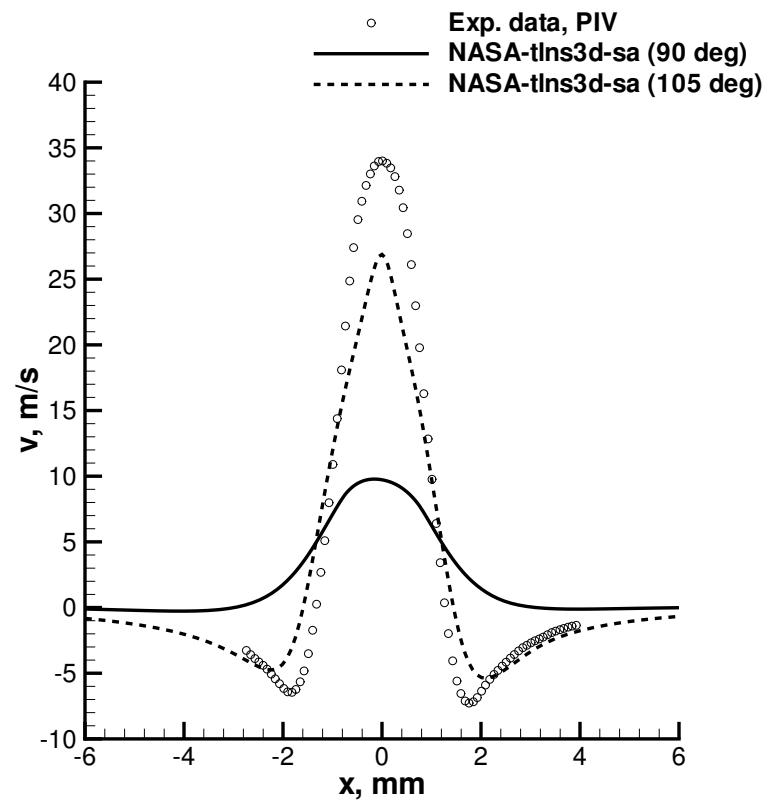
$y = 4 \text{ mm}$



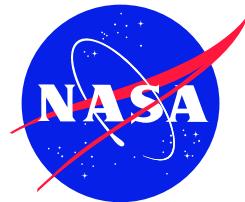
Phase-averaged v-velocity profiles, phase=90



$y = 2 \text{ mm}$



$y = 4 \text{ mm}$



Concluding Remarks

- Assessed the feasibility of using TLNS3D URANS CFD solver to simulate unsteady flow due to a synthetic jet in quiescent air
- Examined the effect of numerical (truncation errors)
 - Effect of refining workshop grid # 1 was minimal. However, halving this grid in both direction had small but noticeable effect
 - Halving the time-step from baseline case insignificant
 - Menter's 2-eqn. SST model produced somewhat smaller spreading rate and jet-width compared to the SA turbulence model
- Comparison with experimental data for phase-averaged quantities qualitative. Matching phase angles with the experimental data tedious
 - Time-variation of PIV data at slot exit not sinusoidal
 - CFD time-histories are much closer to sinusoidal
 - Cause of discrepancy not clear